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## Empirical Calibration of the Physical Parameters of Solar-like stars using *uvby*-Strömgren Photometry

G. Dalle Mese,<sup>1</sup> O. López-Cruz,<sup>1</sup> W. J. Schuster,<sup>2</sup> C. Chavarría-K<sup>2</sup>, J. G. García<sup>2†</sup>

<sup>1</sup> *Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), Luis Enrique Erro 1, C.P. 72840, Tonantzintla, Puebla, México*

<sup>2</sup> *Instituto de Astronomía, UNAM. Apartado Postal 877, Ensenada, B.C., C.P. 22800, México*

**Abstract.** We present an empirical calibration of the physical parameters of A, F and early G-type stars of luminosity class V. We have used a statistical approach based on a sample of about 15 000 stars having both *uvby*-Strömgren photometry (Hauck & Mermilliod 1998) and spectral types taken from SIMBAD. Stars closer than 70 pc have been considered reddening-free. In this paper we present the results for 1900 stars within 70 pc. Mean unreddened measurements have been used as input to CHORIZOS (Maíz-Apellániz 2004). By assuming “solar metallicity” ( $[\text{Fe}/\text{H}]=0$ ), we have been able to determine effective temperatures ( $T_{\text{eff}}$ ) and surface gravities ( $\log g$ ) for each spectral type. We have found a tight correlations among the observations and the derived physical parameters; for example,  $T_{\text{eff}}$  can be expressed as a cubic polynomial in  $(b - y)_0$ . From the distribution of colors and indices for 128 stars and their associated physical parameters we have proposed an alternative definition for solar-analogs: stars whose classification is G2 V with  $(b - y)_0 = 0.3927 \pm 0.0190$ ,  $(m_1)_0 = 0.1901 \pm 0.0143$ , and  $(c_1)_0 = 0.3302 \pm 0.0388$ ,  $T_{\text{eff}} = 5930 \pm 145$ , and  $\log g = 4.70 \pm 0.33$ . These values are consistent with previous empirical results; however,  $(m_1)_0$  differs from a recent model-based value for this index derived by Meléndez et al. (2010). This discrepancy points out the actual solar metallicity problem. We suggest that our sample of solar analogs could be useful for searches of solar twins and exoplanets.

### 1. Introduction

Intermediate-band photometry has clear advantages over broad-band photometry: its results are closer to those of low-resolution spectroscopy and allow the separation of stellar physical parameters such as temperature, surface gravity and metallicity. Specifically, the *uvby*-Strömgren system (Strömgren 1966) was carefully defined to closely match and reproduce stellar spectral types. This system considers the following linear combinations of indices:  $c_1 = (u - v) - (v - b)$ , and  $m_1 = (v - b) - (b - y)$ , which measure the Balmer Jump and line blanketing for A-G type stars, respectively. As the stellar physical properties change with spectral type,  $c_1$  is a good temperature indicator for O to A-type stars, but becomes a luminosity indicator for A to F-type stars. A similar behavior is exhibit by the  $m_1$  index working as a metallicity or peculiarity indicator around A-type stars, but as a chemical composition indicator for F to G-type stars. The color  $(b - y)$  is sensitive to temperature but not metallicity (because of comparable and

small line blanketing in  $b$  and  $y$ ) and the  $(v - b)$  color is very sensitive to metallicity for F and G stars due to larger blanketing in  $v$ .

### 1.1. The MK System of Spectral Classification

The MK is an autonomous and self consistent system of spectral classification. It relies on a well-defined set of standard stars, chosen on the basis of the phenomenology of spectral lines, blends, and bands, according to a general progression of color index (abscissa) and luminosity (ordinate) (Morgan & Keenan 1973). The standard stars define an array that is located on the two-dimensional spectral type vs. luminosity class diagram.

Below we show that the  $uvby$ -Strömgren photometric system does reproduce MK spectral types. We found that the distribution of colors and indices for each spectral type permits the definition of photometric classification boxes. MK types can be assigned unambiguously within two spectral subclasses. We have derived the physical parameters using mean color and indices by spectral type. We have found a new calibration for  $T_{eff}$  and  $(b - y)_0$ . These results have allowed us to provide an alternative definition for solar analogs.

## 2. Observational Data

The compilation of Strömgren photometric measurements from Hauck & Mermilliod (1998), that contains  $\sim 63\,000$  stars was cross-matched with the *Set of Identifications, Measurements, and Bibliography for Astronomical Data* (SIMBAD), the HIPPARCOS database (Perryman et al. 1997) to produce a list of stars with photometric colors and indices, spectral types, and parallaxes. Our final sample with reliable spectral types (A0 V to G5 V) and photometric measurements ( $V \lesssim 18^m.0$  for G2 V stars) contains  $\sim 15\,000$  stars.

## 3. Interstellar Reddening

Understanding the local interstellar reddening is of fundamental importance in the derivation of the  $(b - y)_0$  calibration, and likewise for stellar metallicities, distance and ages. The nearest interstellar dust patches are at about 70 pc in some particular directions, this region devoid of dust is commonly identified with the *Local Hot Bubble*. Indeed, several investigations indicate that the effects of interstellar reddening are almost negligible for stars closer than 70 pc from the Sun (e.g., Tinbergen 1982; Leroy 1999; Holmberg et al. 2007; Luck & Heiter 2007). In this work we present the analysis for 1900 stars within 70 pc from the Sun; since no correction for extinction is needed their colors and indices are taken as they are (i.e.,  $(b - y) = (b - y)_0$ ,  $m_1 = (m_1)_0$ , and  $c_1 = (c_1)_0$ ). The rest of the stars were corrected for galactic extinction as described in Crawford (1975) and Schuster & Nissen (1989). A full analysis on the total sample of 15 000 stars will be presented elsewhere.

## 4. The Distribution of Observed Properties

We have generated the distributions of colors and color indices by spectral type for main sequence stars from A0 to G5. In Figure 1 we show that the distribution of colors and

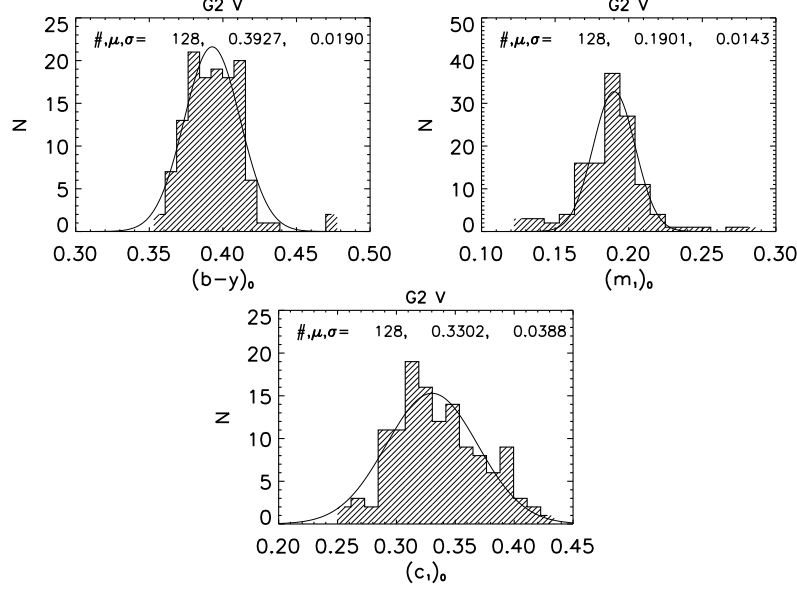


Figure 1. The panels show the statistical distribution of the Strömgren photometric indices for nearby G2 V stars (distances <70 pc). The mean values of these distributions are:  $(b-y)_0 = 0.3927 \pm 0.0190$ ,  $(m_1)_0 = 0.1901 \pm 0.0143$  and  $(c_1)_0 = 0.3302 \pm 0.0388$ . With these values we can provide an alternative definition for solar analogs, see the text for details.

indices for G2 V stars closely follow Gaussian distributions. This is expected given the discreteness of the spectral types, the small photometric errors reported (of the order of a thousandth of a magnitude), the size of the sample considered (up to 200 stars per spectral type), and the De Moivre-Laplace Theorem. Highly discordant values will occupy the tails of the distribution while most of the values will cluster around the mean, as the number of stars gets larger the distribution becomes narrower. We should note that the entrances in the Hauck & Mermilliod (1998) catalog are weighted values, while the spectral types were taken from different sources in the literature.

The mean values and widths ( $\sigma$ ) of the distribution of measured color and indices can be read directly from Table 1. The distributions of spectral types shows a paucity at A5 V to A6 V, this was pointed out by Houk (1984), we have neglected A6 V stars because only four stars were found in Hauck & Mermilliod (1998) within 70 pc. If we consider these mean values and their widths for the distribution of  $(b-y)_0$  by spectral type; then, we can classify stars with a resolution of two spectral classes for stars of luminosity class V. We have checked the Strömgren color and indices for the MK standard stars in the grid defined by López-Cruz (1991). We found that the published values fall within  $1\sigma$  from the mean values for the corresponding spectral type. Hence, we suggest that our statistical approach provides an accurate way to determine MK types photometrically.

Figure 2 shows the distribution for the 1900 A0-G5 V stars in the  $(c_1)_0$  vs.  $(b-y)_0$  diagram. The broadening in  $(c_1)_0$  is produced by surface gravity (e.g., Lester et al. 1986); hence, in this diagram we can appreciate the sensitivity of the spectral classification to surface gravity. As expected, for main sequence stars, the Balmer Jump

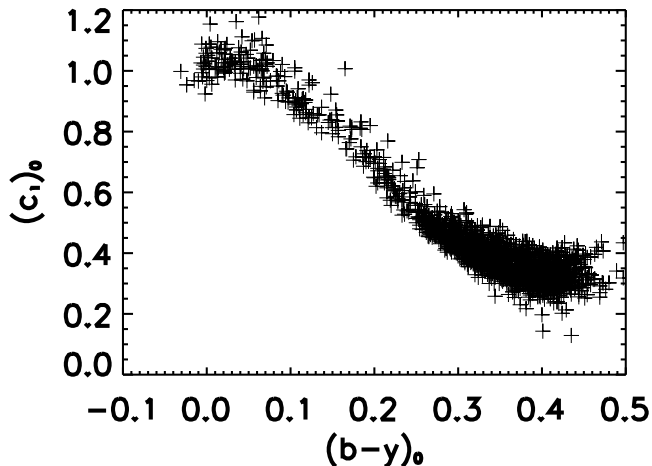


Figure 2. The locus of A0-G5 dwarfs in the  $(c_1)_0$ ,  $(b-y)_0$  plane.  $(c_1)_0$  measures the Balmer Jump (surface gravity) and  $(b-y)_0$  the temperature. We expect to find a maximum at  $(b-y)_0 \sim 0$  and, if observed values of  $(b-y)_0$  are used, some scatter toward larger values of this index is due to interstellar reddening.

reaches its maximum around A0 V stars. For earlier than A0 stars the  $(m_1)_0$  is no longer a surface gravity indicator, it becomes a temperature indicator, instead.

The results presented here are in agreement and complement the results of Crawford (1984). Table 1 is in close agreement, but improves over the results of Oblak et al. (1976) due to better sampling for some spectral types and better handle on the reddening correction.

## 5. Physical Parameters

We have used CHORIZOS (Maíz-Apellániz 2004) to obtain  $T_{eff}$  and  $\log g$ . This code compares photometric data of a star with model spectral-energy distributions. The code calculates the likelihood for the full specified parameter ranges (extinction, temperature, gravity, metallicity), thus allowing for the identification of multiple solutions and the evaluation of the full correlation matrix for the derived parameters of a single solution.

The input parameters that we used were the mean *uvby*-Strömgren colors of each spectral type with their respective uncertainties and a family of spectral-energy distributions (SED) of Kurucz with the following parameters:  $T_{eff} = [3500, 50000]K$ ,  $\log g = [0.0, 5.0]$ ,  $\log(Z/Z_\odot) = [-1.5, 0.0]$ ,  $E(B-V) = [-0.5, 5.0]$  and the total to selective extinction ratio for the interstellar medium of  $R_V = 3.1$ . CHORIZOS performs a  $\chi^2$  analysis to assign a likelihood to each of the models in a  $N$  dimensional space by comparing the observed and the set of modeled colors. In our case,  $\log(Z/Z_\odot) = 0$ ,  $E(B-V) = 0$  where held fixed. The results are presented in Table 1, columns 8 and 9. The errors are given by CHORIZOS, they are meant to represent the range of values for each spectral type.

Table 1. Average Photometric Strömgren Colors and Indices by MK spectral types

Spectral Type	$(b-y)_0$	$\sigma(b-y)_0$	$(m_1)_0$	$\sigma(m_1)_0$	$(c_1)_0$	$\sigma(c_1)_0$	$T_{eff}$ (K)	$\log g$ $cm/s^2$
A0 V	0.0004	0.0140	0.1609	0.0256	1.0317	0.0646	9949 $\pm$ 405	4.41 $\pm$ 0.39
A1 V	0.0177	0.0205	0.1786	0.0140	1.0043	0.0431	9672 $\pm$ 383	4.41 $\pm$ 0.31
A2 V	0.0306	0.0261	0.1802	0.0222	1.0241	0.0333	9445 $\pm$ 442	4.37 $\pm$ 0.32
A3 V	0.0559	0.0186	0.1835	0.0150	1.0114	0.0837	8907 $\pm$ 420	4.52 $\pm$ 0.36
A4 V	0.0705	0.0131	0.1928	0.0119	0.9432	0.0739	8647 $\pm$ 273	4.54 $\pm$ 0.32
A5 V	0.0957	0.0301	0.1919	0.0162	0.9514	0.0331	8458 $\pm$ 506	4.33 $\pm$ 0.30
A7 V	0.1136	0.0116	0.1997	0.0147	0.9054	0.0351	8109 $\pm$ 259	4.11 $\pm$ 0.28
A8 V	0.1502	0.0115	0.1825	0.0081	0.8326	0.0856	7747 $\pm$ 206	4.34 $\pm$ 0.37
A9 V	0.1781	0.0488	0.1717	0.0148	0.7605	0.1067	7623 $\pm$ 569	4.63 $\pm$ 0.35
F0 V	0.1980	0.0387	0.1690	0.0236	0.7133	0.1048	7423 $\pm$ 414	4.67 $\pm$ 0.36
F1 V	0.2221	0.0552	0.1619	0.0121	0.6144	0.0897	7261 $\pm$ 538	4.66 $\pm$ 0.33
F2 V	0.2551	0.0340	0.1531	0.0137	0.5412	0.0793	7000 $\pm$ 325	4.59 $\pm$ 0.37
F3 V	0.2715	0.0147	0.1492	0.0112	0.4800	0.0385	6874 $\pm$ 148	4.39 $\pm$ 0.37
F4 V	0.2899	0.0218	0.1563	0.0252	0.4644	0.0466	6713 $\pm$ 199	4.50 $\pm$ 0.40
F5 V	0.2988	0.0153	0.1538	0.0103	0.4324	0.0431	6649 $\pm$ 145	4.45 $\pm$ 0.40
F6 V	0.3196	0.0166	0.1546	0.0123	0.4149	0.0523	6478 $\pm$ 145	4.53 $\pm$ 0.40
F7 V	0.3345	0.0165	0.1587	0.0134	0.3881	0.0432	6362 $\pm$ 143	4.56 $\pm$ 0.39
F8 V	0.3499	0.0152	0.1678	0.0132	0.3755	0.0472	6244 $\pm$ 121	4.60 $\pm$ 0.38
F9 V	0.3600	0.0164	0.1687	0.0199	0.3477	0.0480	6171 $\pm$ 137	4.66 $\pm$ 0.35
G0 V	0.3733	0.0172	0.1757	0.0136	0.3429	0.0413	6068 $\pm$ 134	4.67 $\pm$ 0.34
G1 V	0.3832	0.0161	0.1862	0.0220	0.3417	0.0394	6001 $\pm$ 118	4.68 $\pm$ 0.34
G2 V	0.3927	0.0190	0.1901	0.0143	0.3302	0.0388	5930 $\pm$ 145	4.70 $\pm$ 0.33
G3 V	0.4042	0.0171	0.1979	0.0179	0.3336	0.0417	5847 $\pm$ 133	4.71 $\pm$ 0.32
G4 V	0.4130	0.0153	0.2099	0.0186	0.3284	0.0385	5787 $\pm$ 108	4.73 $\pm$ 0.31
G5 V	0.4253	0.0175	0.2220	0.0229	0.3168	0.0347	5715 $\pm$ 125	4.74 $\pm$ 0.30

## 6. Results

The main results from this work are presented in Table 1. We can see a clear progression between  $(b-y)_0$  and  $T_{eff}$ , a simple fit to third order polynomial accounts for temperature variations in the range between A0 V and G5 V stars. The fit is given by the following expression (see Figure 3):

$$T_{eff} = 9955.49(\pm 38.79) - 20010.40(\pm 843.26)(b-y)_0 + 45881.00(\pm 4589.29)(b-y)_0^2 - 53299.20(\pm 6944.62)(b-y)_0^3. \quad (1)$$

These results should be taken with the caveat that our statistical approach overlooks for the effects of rotation, magnetic fields, metallicity and that the derived physical parameters come from unidimensional model atmospheres in LTE. However, we have found a nice correspondence among spectral types,  $(b-y)_0$ , and  $T_{eff}$ . Equation 1 is in agreement with previous calibrations (e.g., Alonso et al. 1996; Gray et al. 2001; Clem et al. 2004). However, we find that our result for the index  $(m_1)_0$  is inconsistent with the solar value calculated by Meléndez et al. (2010). We may explain this discrepancy in the apparent problem with the solar metallicity that has pervaded in the literature and was discussed during this conference. The newest 3D model atmospheres have changed the abundance value for the Sun (e.g., Asplund et al. 2009).

### 6.1. An Alternative Definition for Solar Analogs

The Sun has never been classified using a regular telescope and spectrograph. It always appears resolved and the effects of limb darkening, rotation, variability creep in

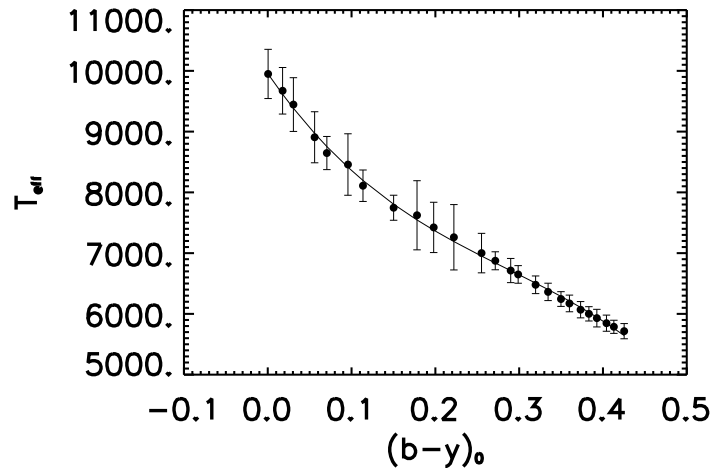


Figure 3. Relation between the derived  $T_{eff}$  and  $(b-y)_0$  index for A0 V to G5 V stars of Table 1, each point represents an spectral type, errors in the calibrated temperature are given by CHORIZOS (cf., Clem et al. 2004), the solid line is a cubic polynomial fit:  $T_{eff} = 9955.49(\pm 38.79) - 20010.40(\pm 843.26)(b-y)_0 + 45881.00(\pm 4589.29)(b-y)_0^2 - 53299.20(\pm 6944.62)(b-y)_0^3$ .

hampering the classification\*. Alternative standards for the G2 V type have been considered, for example, HR483, Jupiter IV and 18 Sco, among others. Depending on adopted set of standards, apparent differences in the photometric colors may arise for each spectral type (E. Mamajek, private communication).

There is a lively discussion regarding the definition of a solar twin, that is a star with mass, chemical composition, age,  $T_{eff}$ ,  $\log g$ , luminosity, magnetic fields, velocity fields, equatorial rotation, etc. very similar if not identical to those of the Sun (Cayrel de Strobel 1996). However, it has been argued that no solar twin has yet been found (Strassmeier 2004) and the search seems to be far from over (e.g., Gray & Corbally 2009). Nevertheless, the general consensus is that 18 Sco is the best solar twin candidate.

We wish to introduce an alternative definition from that of Cayrel de Strobel (1996) for solar analogs. We propose that G2 V stars with  $(b-y)_0 = 0.3927 \pm 0.0190$ ,  $(m_1)_0 = 0.1901 \pm 0.0143$ , and  $(c_1)_0 = 0.3302 \pm 0.0388$  whose  $T_{eff} = 5930 \pm 145$  and  $\log g = 4.70 \pm 0.33$  should be considered solar analogs. This could help to narrow down the searches for solar twins. Solar twins are an important piece in the understanding of the origin of our solar system.

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\*Prof. Robert F. Garrison used to start his lectures of G stars by stating that the worse classified star in the MK system was the Sun. He taught a graduate course on stellar classification for many years at the University of Toronto.

## 7. Concluding Remarks

- We have shown the effectiveness of the Strömgren system in the investigation on the physical properties of stars, avoiding the degeneracies inherent to broad band photometry. We will apply this technique to stellar clusters and galaxies.
- We have introduced a technique that allows the derivation of accurate  $T_{eff}$  for main sequence stars from a comparison of mean reddening-free photometric indices for  $\sim 1900$  stars with a grid of synthetic spectra and fluxes computed from Kurucz models. The  $T_{eff}$  can be expressed as a cubic polynomial in  $(b-y)_0$ . Our calibration is in agreement with previous ones (e.g., Alonso et al. 1996; Gray et al. 2001; Clem et al. 2004).
- From the distribution of colors and indices for 128 stars and their associated physical parameters we have proposed an alternative definition for solar-analogs: stars whose classification is G2 V with  $(b-y)_0 = 0.3927 \pm 0.0190$ ,  $(m_1)_0 = 0.1901 \pm 0.0143$ , and  $(c_1)_0 = 0.3302 \pm 0.0388$ ,  $T_{eff} = 5930 \pm 145$  and  $\log g = 4.70 \pm 0.33$ .

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